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SHEAR WAVE GENERATION FROM CONTAINED EXPLOSIONS

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13. ABSTRACT *(Maximum 200 words)*

The usefulness of the amplitude ratio of seismic phases such as Lg/P, as well as the ratio of magnitudes (e.g. Mb/Ms) to discriminate explosions from earthquakes depends, in part, on the efficiency of shear wave production from seismic sources. We are studying shear wave generation at the source, initially from explosions within limestone blocks. Initially the samples are subjected to hydrostatic stress. However, we will be able to also simulate tectonic strain energy release in future experiments. Using a 1.6 m long, 0.8 m diameter sample subjected to an ambient pressure of up to 1 MPa, with a centrally placed explosive source, we propose to study the amplitude of shear wave generation of stress-wave induced radial cracking in symmetric and asymmetric cavities. In unstressed rock, this shear wave production is expected to be controlled in part by the natural anisotropy of the rock (e.g. bedding). We expect to measure the S/P ratio from tamped explosions using (0.2 to 2 gram charges). Later tests will be conducted in partially decoupled asymmetric cavities, and the resultant shear wave radiation pattern will be compared to previous detailed finite element calculations of P and S wave radiation versus frequency and angle for elliptical cavities of aspect ratios in the range of 1:3 to 1:10 conducted by Glenn et al. [1985]. In order to measure the P and S waves generated from explosions, we developed a measurement method that is given in detail in this report. The initial test results for the tamped and decoupled explosions in cylindrical cavities in limestone show that the amplitude of SV/P for the decoupled experiment in limestone is ~0.7, whereas it varies over a range of ~1 to 3 for overdriven cavities, depending on angle from the cylindrical axis. Moreover, tensional cracks are generated in these cavities which resemble those inferred to have occurred in a similar geometry in the Sterling experiment.

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confined explosions, rocks, shear wave generation, discrimination

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1 OBJECTIVES

We are conducting small-scale explosive experiments to test discrimination theories of shear wave generation from explosions in symmetric and asymmetric cavities in rocks. Small PETN charges are detonated in symmetric and asymmetric cavities, within meter-sized samples of limestone, shale, and other rock types. We constructed an apparatus (Figures 1, 2 and 5) to measure shear wave generation both from the asymmetric stress imposed on the explosion cavity walls by detonation, as well as from the cracking of the rock. We also expect to develop a theoretical model of these effects. We expect to apply Brune's (U. Nevada) and L. Glenn's (LLNL) model of the stresses from such cavities to test discrimination algorithms.

We have developed sealing methods for conducting the test under ~ 1 MPa of water pressure, as shown in Fig.5. Initially rock samples of Bedford limestone were employed in the initial tests that are discussed below.

2 RESEARCH ACCOMPLISHED

2.1 Introduction

In the past 30 years, extensive research has been conducted on the discrimination of underground explosions from earthquakes. As a result, Murphy (1996) recently concluded that the seismology of earthquakes and underground explosions is at a state that it is possible to identify tamped explosions with the yield over 1 kiloton ($m_b \geq 4$) on a world-wide basis. These explosions can be distinguished from earthquakes by the global seismic stations using the initial P-wave motion and the M_s to m_b ratio. In fact, the discrimination of the tamped explosions from earthquakes depends mainly on the collection of the seismic data from previous underground nuclear explosions. However, many basic problems related to tamped explosions still remain unsolved (Masse, 1981; Murphy, 1996), e.g., the generation of long period Rayleigh waves ($\geq$ 5 seconds), SH-waves and Love-waves etc. But now, the most difficult problem is to distinguish earthquakes from decoupled explosions with complex geometries.

The characteristics for decoupled explosions (Murphy, 1996) are: (1) m_b is too low to use the global monitoring system (in general, $m_b \leq 3$); (2) the amplitude of surface waves generated in the explosions is much less than it is from the tamped explosions(it is hard to distinguish it from white noise); (3) the excitation of direct SV-waves and possible SH-waves makes the problem more difficult. Although there are many published papers related to the decoupled explosions (Glenn et al., 1985, 1993, 1994, 1996; Murphy et al. 1996; Murphy, 1996; Sykes, 1996; Langston, 1983 etc.), it still is unclear what really controls the generations of S-waves in decoupled explosions (Murphy, 1996). Therefore, the mechanism of S-wave generation from explosions, especially from decoupled explosions is the fundamental question for discrimination.

The suggested possible sources for S-waves from explosions include: (1) the dynamic radial fracture of the rocks near explosions; (2) the asymmetric plastic deformation near the explosion due to the asymmetric geometry and anisotropy of the rocks; (3) tectonic release of shear energy triggered by shock waves from the explosions; (4) the conversion of P-waves to S-waves at the free surface of the Earth. These mechanisms must be studied separately using different methods.

The objective of this work is to investigate shear-wave generation from dynamic fracture and the conversion of shock waves to P- and S-waves on the inner surfaces of the cavities by examining the relationship between the geometry and the amplitude distribution of the S-waves generated from confined explosions in rocks in the laboratory. For symmetric or asymmetric explosions, if the shock wave pressure is not too high, the rocks near explosions will fail via brittle fracture mechanisms. Radial fractures may be initiated from the inner surface of the cavity because the tangential(hoop) stresses always achieve the maximum on the surface. This radial fracture generally is further driven by the high-pressure explosive products (Coursen, 1985). In asymmetric explosions, the reflection of the shock waves from the inner cavity surface will also produce S-waves. The amplitude of the S-waves depends on the incident angle and generally increases with the incident angle for angles below the critical reflection angle.

In order to investigate the details of the S-wave generation from tamped and decoupled explosions in rocks, we need first to develop a measurement method that can be used to monitor both P- and S-waves generated in explosions. For small-scale laboratory experiments, the wave profiles have relatively higher frequencies than the usual seismic waves. Therefore, the conventional seismic recording system can not be used to measure those wave profiles. One candidate method developed for super-high strain rate experiments (Kim and Clifton, 1977) is difficult to employ for the present experiments because it requires special treatment of samples. Magnetic velocity gauges have been used to study shock wave decays in rocks, but this method requires embedding the gauges in the rock. This adds some artificial interfaces which will make the S-wave data more complicated. Based on the analysis of the interaction between P- and S-waves and free surfaces, we have developed a method to measure P- and S-wave profiles on the free surfaces of rocks. The main idea of the method is to use the different characteristics of the interactions between P- and S-waves and the free surface. The method and the experimental data from this method are presented below.

2.2 Measurement Method

When P- and S-waves arrive at the free surface, the interactions between the P- and S-waves and the free surface are very different. The characteristics of these interactions provide the opportunity to measure the incident P- and S-wave amplitudes from the strain measurements on the free surfaces of rocks. The method developed is to use two strain gauges to measure the strains along two perpendicular directions at one point on the free surface of the rocks. The incident amplitude of P- and S-waves can be obtained from these strain measurements.

The basic assumptions made for the method are:

1. The waves in the rocks can be approximately treated as locally plane waves.

2. The deformation of the rocks near the free surface is elastic.

2.3 Sensors

A group of strain gauges are employed to monitor the wave profiles at different locations along two directions on the free-surface of rock samples. The directions of the gauges are shown in Figure 1. The block diagram of the recording system is shown in Figure 2. The gauges and amplifiers are powered by batteries in order to achieve a high signal/noise ratio. A mercury relay is used to calibrate the system. The relation between strains, ε, and voltages change, ΔV, is

$$\varepsilon = \frac{\Delta V}{fgV_0}, \tag{1}$$

where V_0 is the initial voltage supplied on the gauges. f and g are the gauge factor and gain of the amplifiers, respectively.

2.4 Data Reduction Method

Strain gauges give the elongation along the gauge directions. When they are attached on a free surface, they measure the elongation of the free surface after wave reflections. The strains recorded by the gauges include the contributions from incident P- and S-waves and the reflected P- and S-waves. In order to get the relation between the strains given by the gauges and the incident P- and S-wave amplitudes, we first conducted an analysis of the interactions between the incident P- and S-waves and the free surfaces.

2.4.1 The P-wave Reflection at Free Surfaces

The displacement reflection coefficients for incident P-waves at free surfaces (Aki and Richards, 1980) are

$$PP = \frac{B-A}{B+A}, \tag{2}$$

$$PS = \frac{2\frac{\beta}{\alpha}\sin(2\theta)\cos(2j)}{A+B}, \tag{3}$$

where PP and PS are the reflection coefficients for P- and SV-wave displacements due to the incident P-waves, respectively. α and β

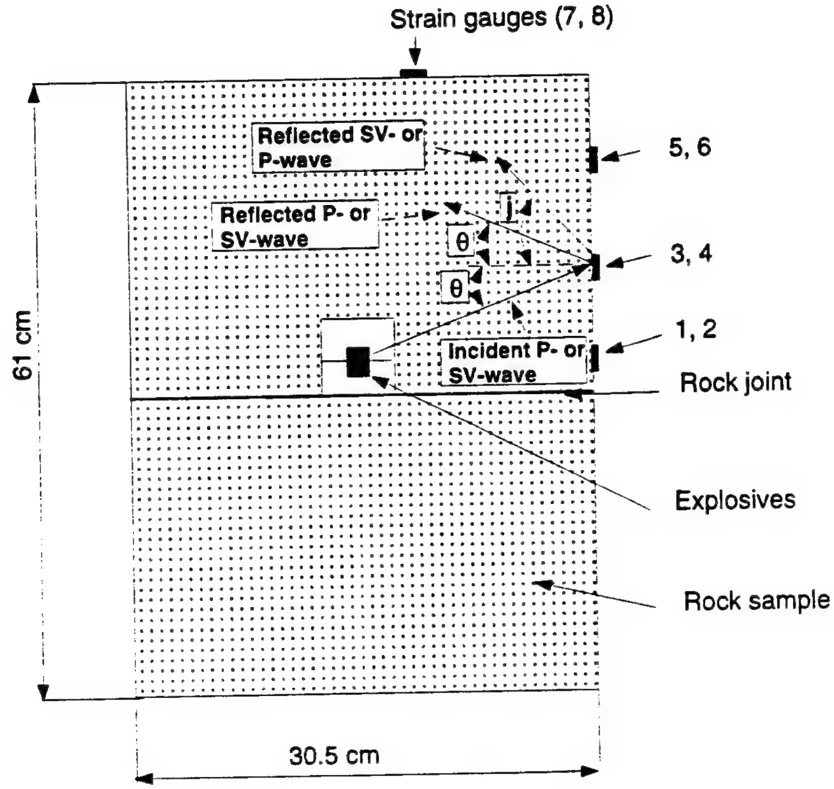


Figure 1 (A) Layout of rock sample, strain gauges and explosive charge

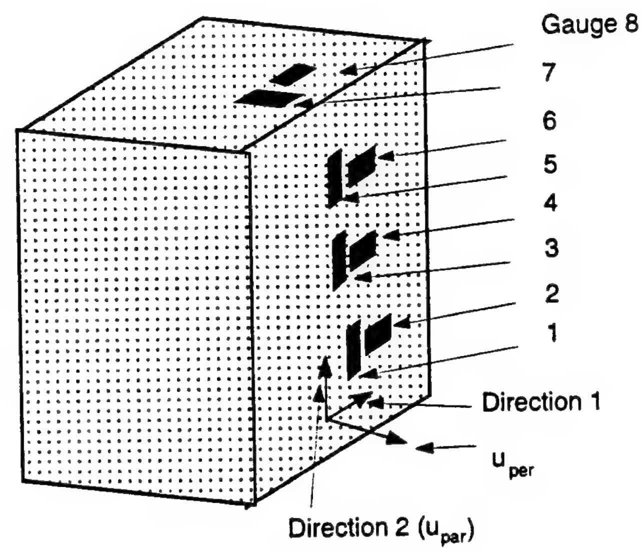


Figure 1 (B) Sketch of polarization directions of strain gauges

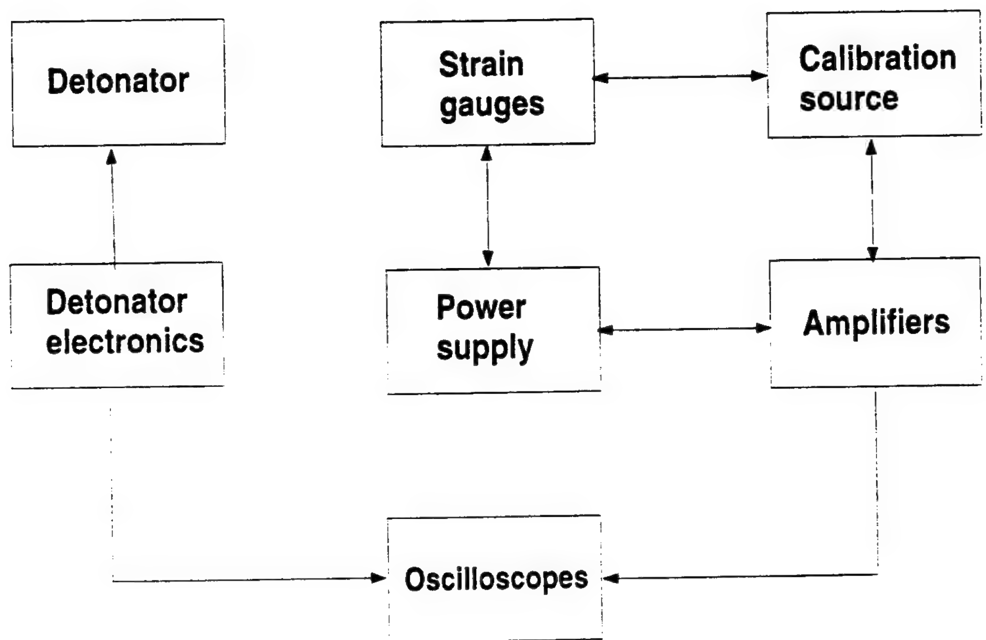


Figure 2 Recording system of the experiments

are P- and S-wave velocities, respectively. A and B are

$$A = \cos^2(2j), \tag{4}$$

$$B = (\frac{\beta}{\alpha})^2 \sin(2j)\sin(2\theta), \tag{5}$$

where θ and j are the P-wave incident angle and S-wave reflection angle, respectively. The θ and j are shown in Figure 1.

$$\sin j = \frac{\beta}{\alpha}\sin\theta, \tag{6}$$

$$\cos j = (1 - (\frac{\beta}{\alpha})^2 \sin^2 j)^{\frac{1}{2}}. \tag{7}$$

The resultant displacements of the particles on the free surfaces after the reflection are

$$u^p_{par} = u^I_p[(1+PP)\sin\theta + PS\cos j] = H_{par}u^I_p, \tag{8}$$

$$u^p_{per} = u^I_p[(1-PP)\cos\theta + PS\sin j] = H_{per}u^I_p, \tag{9}$$

where u^I_p is the particle displacement of the incident P-wave, u^p_{par} and u^p_{per} indicate the resultant particle displacements along direction 2 and the direction that is perpendicular to the free surface after reflection as shown in Figure 1, respectively. The H_{par} and H_{per} are

$$H_{par} = (1+PP)\sin\theta + PS\cos j, \tag{10}$$

$$H_{per} = (1-PP)\cos\theta + PS\sin j. \tag{11}$$

Substituting all the definitions into the equations, Eqs.(10) and (11) can be rewritten as

$$H_{par} = \frac{2\cos\theta\sin(2j)}{A+B}, \tag{12}$$

$$H_{per} = \frac{2\cos\theta\cos(2j)}{A+B}. \tag{13}$$

2.4.2 The SV-wave Reflection at Free Surfaces

For incident SV-waves, the displacement reflection coefficients for P- and SV-waves (Aki and Richards, 1980) are

$$SP = \frac{\frac{\beta}{\alpha}\sin(4\theta)}{A_s + B_s}, \tag{14}$$

$$SS = \frac{A_s - B_s}{A_s + B_s}, \tag{15}$$

where SS and SP are the reflection coefficients of SV- and P-wave displacements due to the incident SV-waves.

$$A_s = \cos^2(2\theta), \tag{16}$$

$$B_s = (\frac{\beta}{\alpha})^2 \sin(2\theta)\sin(2j), \tag{17}$$

where θ and j are the SV-wave incident angle and P-wave reflected angle, respectively, and

$$\cos j = (1 - (\frac{\alpha}{\beta})^2 \sin^2\theta)^{\frac{1}{2}}. \tag{18}$$

The resultant displacements of the particles on the free surfaces after the reflection are

$$u_{par}^{sv} = u_{sv}^I[(1 + SS)\cos\theta + SP\sin j] = G_{par}u_{sv}^I, \tag{19}$$

$$u_{per}^{sv} = u_{sv}^I[(SS - 1)\sin\theta - SP\cos j] = G_{per}u_{sv}^I, \tag{20}$$

where u_{par}^{sv} and u_{per}^{sv} are the resultant particle displacements on the free surface after reflection along direction 2 as shown in Figure 2 and the direction that is perpendicular to the free surface, respectively. u_{sv}^I is the particle displacement of the incident SV-wave. The G_{per} and G_{par} are

$$G_{par} = (1 + SS)\cos\theta + SP\sin j, \tag{21}$$

$$G_{per} = (SS - 1)\sin\theta - SP\cos j. \tag{22}$$

Substituting all the definitions into the equations, they are rewritten as

$$G_{par} = \frac{2\cos(2\theta)\cos\theta}{A_s + B_s}, \tag{23}$$

$$G_{per} = -2\frac{\frac{\beta}{\alpha}\cos j\sin(2\theta)}{A_s + B_s}. \tag{24}$$

2.4.3 Strains Due to Incident P-waves

1. Strains given by the gauges along direction 1

   Because u^p_{per} is perpendicular to the free surface and along the symmetrical axis direction of the waves, the strain due to u^p_{per} along direction 1 is simply expressed as

$$\varepsilon_1^{per} = \frac{H_{per}}{r_0} u_p^I, \tag{25}$$

   where ε_1^{per} is the strain along direction 1 induced by u^p_{per}, and r_0 is the distance from the center of the cavity to the free surface at $\theta = 0$.

   Because u^p_{par} does not result in any strains in the gauges along direction 1 at any time, the total strain induced by the incident P-waves is

$$\varepsilon_1^p = H_1 u_p^I, \tag{26}$$

   where $H_1 = \frac{H_{per}}{r_0}$.

2. Strains given by the gauges along direction 2

   Because u^p_{per} and u^p_{par} all have contributions to the strain given by the gauges along direction 2, we need to consider the resultant displacements.

   The length of the gauge after the reflection, Δs, is

$$\Delta s = (r_n^2 + (\frac{\partial r_n}{\partial \theta})^2)^{\frac{1}{2}} \delta\theta, \tag{27}$$

   where

$$\delta\theta = \frac{l_s}{r_n}, \tag{28}$$

   and l_s is the initial length of strain gauges. r_n is the distance from the center of the cavity to the position of the gauge after reflections

$$r_n = r + u\cos(\eta - \theta), \tag{29}$$

   where r is the distance from the center of the cavity to the gauge before P-wave reflection, u is the resultant displacement

of the point at θ on the free surface and η is the angle between u and u^p_{per}, they are

$$u = u^I_p \frac{2\cos(\theta)}{A+B}, \tag{30}$$

$$\eta = 2j. \tag{31}$$

To a first-order approximation, Δs, is

$$\Delta \approx ((\frac{r}{\cos\theta})^2 + 2ru^I_p(W(\theta) + \tan(\theta)\frac{dW}{d\theta})^{\frac{1}{2}} \frac{l_s\cos\theta}{r}, \tag{32}$$

where

$$W = \frac{2\cos(\theta)\cos(\eta-\theta)}{A+B}. \tag{33}$$

If $x \ll 1$, we have

$$(1+x)^{\frac{1}{2}} \simeq 1 + \frac{x}{2}. \tag{34}$$

Because $\frac{u^I_p}{r} \ll 1$, after using the approximation above, Δs is

$$\Delta s \approx (r(1+\frac{\tan^2\theta}{2}) + u^I_p(W(\theta)(1-\frac{\tan^2\theta}{2}) + \tan\theta\frac{dW}{d\theta}))\delta\theta. \tag{35}$$

Then the strain is

$$\varepsilon^p_2 = \frac{\Delta s - l_s}{l_s}, \tag{36}$$

and therefore

$$\varepsilon^p_2 = H_2 u^I_p, \tag{37}$$

where

$$H_2 = \frac{(\cos\theta(W(1-\frac{\tan^2\theta}{2}) + \tan\theta\frac{dW}{d\theta})}{(1+\frac{\tan^2\theta}{2})}, \tag{38}$$

and $r_0 = r\cos\theta$.

2.4.4 Strains Induced by Incident SV-waves

Using the same method, all the strains induced by incident SV-waves can be obtained. The final expressions are listed as following:

1. The strains given by the gauges along direction 1 are

$$\varepsilon_1^{sv} = G_1 u_{sv}^I, \tag{39}$$

where

$$G_1 = \frac{G_{per}}{r_0}. \tag{40}$$

2. The strains given by the gauges along direction 2 can be found using the same method as for the incident P-wave. The resultant strains induced by the incident SV-waves along direction 2 are

$$\varepsilon_2^{sv} = G_2 u_{sv}^I, \tag{41}$$

where

$$G_2 = \frac{(\cos\theta(W_s(1 - \frac{\tan^2\theta}{2}) + \tan\theta\frac{dW_s}{d\theta})}{(1 + \frac{\tan^2\theta}{2})}, \tag{42}$$

$$W_s = \frac{2\cos(\eta - \theta)\cos\theta}{A_s + B_s}(\cos^2(2\theta) + 4(\frac{\beta}{\alpha})^2\cos^2 j\sin^2\theta)^{\frac{1}{2}}, \tag{43}$$

$$\tan\eta = -\frac{\alpha\cos\theta}{\beta\cos j\tan(2\theta)}. \tag{44}$$

2.4.5 The Amplitude of Incident P- and SV-waves

From the expressions given above, the displacements of incident P- and SV-waves can be obtained through the strains given by the gauges along the two directions.

1. The displacement of the incident P-waves is

$$u_p^I = \frac{\varepsilon_1^p}{H_1} = \frac{\varepsilon_2^p}{H_2}. \tag{45}$$

2. The displacement of the incident SV-waves is

$$u_{sv}^I = \frac{\varepsilon_{sv}^1}{G_1} = \frac{\varepsilon_{sv}^2}{G_2}. \tag{46}$$

2.4.6 The Characteristics of the Strains Given by Gauges in Bedford Limestone

1. P-waves

   (a) The non-dimensional constant, H_1 in Eq.(45) is not sensitive to the variation in θ, e.g., the value of H_1 is about 2.0 for Bedford limestone. The non-dimensional constant, H_2 in Eq.(45) changes rapidly with θ, it varies from -0.8 to 2 for Bedford limestone as shown in Figure 3.

   (b) From Figure 3, the strains induced by P-waves along direction 1 are always positive, but the strains along direction 2 are positive when θ is less than 47^o and negative when θ is larger than 47^o (for Bedford limestone). This polarity change is controlled by the ratio of the projection of P-wave displacement along direction 1 to that along the direction that is perpendicular to the free surface.

2. SV-waves

   (a) The relation between G_1 (G_2) and the SV-wave incident angle for Bedford limestone is given in Figure 4. From the calculated results, the gauges along direction 1 are not sensitive to incident SV-wave; however, the gauges along direction 2 are very sensitive to incident SV-wave.

   (b) The measurement of SV-waves are limited by the Rayleigh surface wave generation. For Bedford limestone, the Rayleigh wave is generated when θ is larger than about 35^o (determined from Snell's law).

   (c) The polarities of the strains along direction 2 are negative, and the polarities of the strains along direction 1 are determined by the direction of the particle motion (the calculation is made assuming that the motion direction is toward the increasing direction of the SV-wave incident angle).

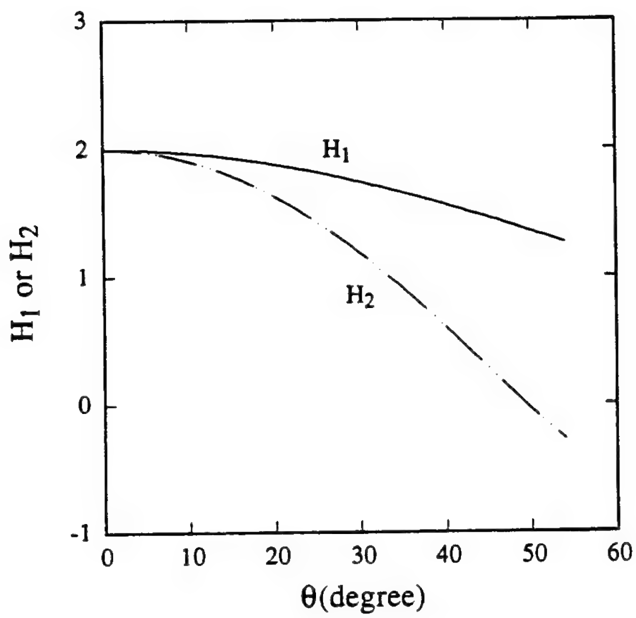


Figure 3 H_1 and H_2 versus P-wave incident angle (θ) in Bedford limestone

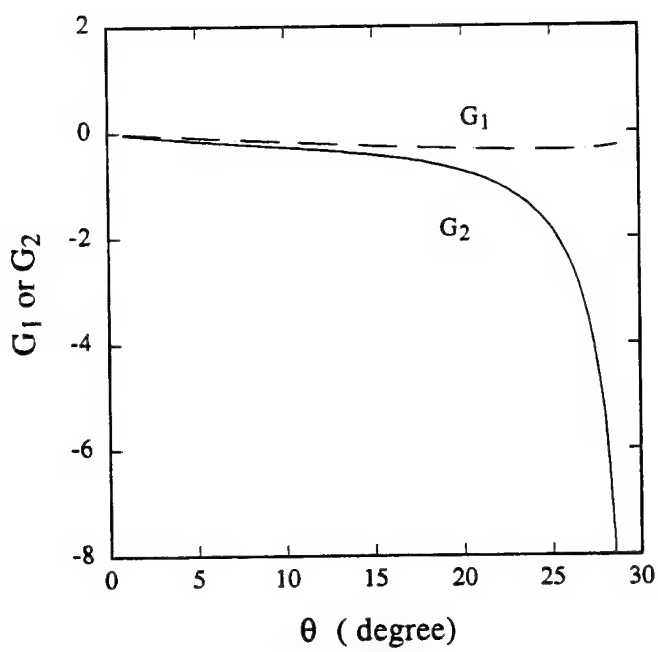


Figure 4 G_1 and G_2 versus SV-wave incident angle (θ) in Bedford limestone

3 Experiments and Results

3.1 Experimental Details

The rock sample (Bedford limestone) is assembled using two blocks as shown in Figure 1. The rock sample with strain gauges is placed inside a tank pressurized to 10 bar. To prevent the sample from becoming invaded by water, a plastic film with 0.21 mm thickness (Vinyl film sheet No. 8562K5, Warp Bros.) is wrapped on the surface of the rocks. The experimental set-up is shown in Figure 5. From the recovered samples, the rocks were still dry after the explosions. The type of strain gauge used in this work is CEA-00-062UT-120 from Measurements Group. The dimensions of the gauges are 3x3 mm. The initial resistance of gauges is 120 Ω $\pm 0.4\%$ and the gauge factor is 2.090 $\pm$ 0.5%. The procedure to attach the gauges on the surface is: (1) The surface is polished with sandpaper (No. 240, 3M); (2) the surface is cleaned using acetone; (3) the gauges are attached on the surface using 910 adhesive (Permabond International); (4) after the adhesive is dried, a thin layer of the epoxy (5-minute epoxy, ITWDevcon) is applied on the gauge surface in order to protect them. The voltage on the gauge is typical 6 V (before each experiment, the voltage on each gauge is measured). The amplifiers used in this work are specially designed to satisfy the requirements of high gain, wide bandwidth and low noise.

The explosive used in this work is PETN. The explosive is placed in a plastic shell(the thickness of the shell is 1 mm, and the inner diameter is the same as the diameter of the explosives) and detonated using a high-voltage detonator (the voltage is about 2000 V). The size of the detonator is ϕ2x8 mm.

3.2 Experimental Results

Two experiments were conducted on Bedford Limestone. One modeled a decoupled explosion and the other a tamped explosion. The parameters used in the experiments are listed in Table 1.

The recorded strains for the two experiments are shown in Figures 6(a) and (b), Figures 7(a) and (b). The characteristics of the strains recorded by the gauges are the same as predicted using the

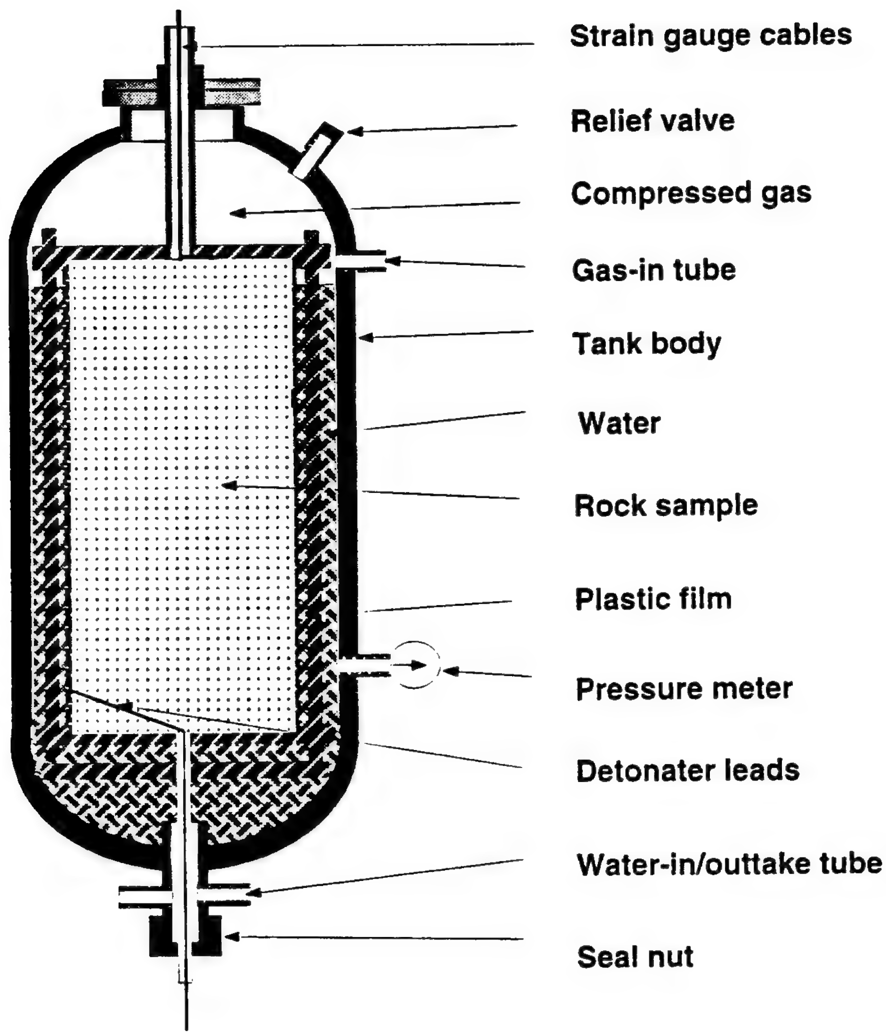


Figure 5 Pressurized test chamber

Table 1: **Parameters used in the experiments**

	dimensions of explosives	mass of explosives	type of explosives	dimensions of cavities
decoupled	ϕ 5x6 mm	0.24 g	pressured PETN	ϕ 30x30 mm
tamped	ϕ10x10 mm	1.2 g	sheet PETN	ϕ 12x12 mm

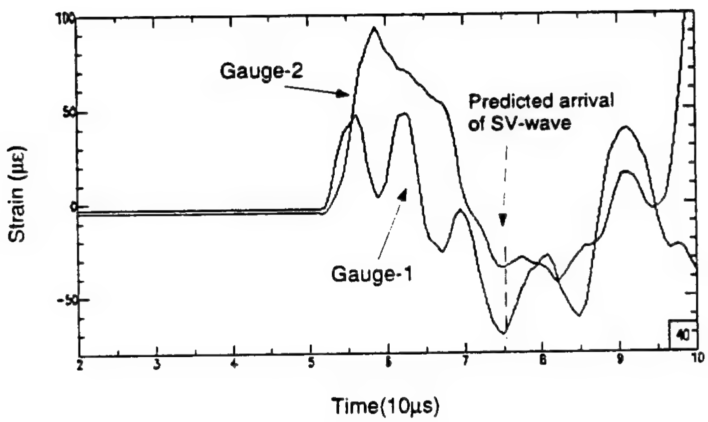
Table 2: **The results for the decoupled experiment**

θ^o	D (mm)	$\varepsilon_{sv}(\mu\varepsilon)$	$t_{sv}(\mu s)$	$\varepsilon_p(\mu\varepsilon)$	$t_p(\mu s)$	$u^I_{sv}(mm)$	$v_{sv}(m/s)$	$u^I_p(mm)$	$v_p(m/s)$	R_u
2.1	153			98	5			0.0072	1.4	
15.3	157	78	8	67	4	0.0055	0.7	0.0043	1.0	0.7
36.4	189			28				0.0019	0.34	

Table 3: **The results for the tamped experiment**

θ^o	D (mm)	$\varepsilon_{sv}(\mu\varepsilon)$	$t_{sv}(\mu s)$	$\varepsilon_p(\mu\varepsilon)$	$t_p(\mu s)$	$u^I_{sv}(mm)$	$v_{sv}(m/s)$	$u^I_p(mm)$	$v_p(m/s)$	R_u
6.4	153	233	8.8	450	16	0.029	3.3	0.035	2.2	1.5
9.8	243	164	11	95	13	0.027	2.4	0.0099	0.8	3
20.9	162	254	12	280	17	0.012	1.0	0.0174	1.0	1.0
36.3	198			140	12.5			0.0092	0.7	

where D is the distance between the gauge and the center of the cavity, t_{sv} and t_p are the times at which the SV- and P-wave induced strains reach the maximum, v_{sv} and v_p are the average particle velocities for SV- and P- waves, R_u is the ratio of SV-wave particle velocity to P-wave particle velocity.



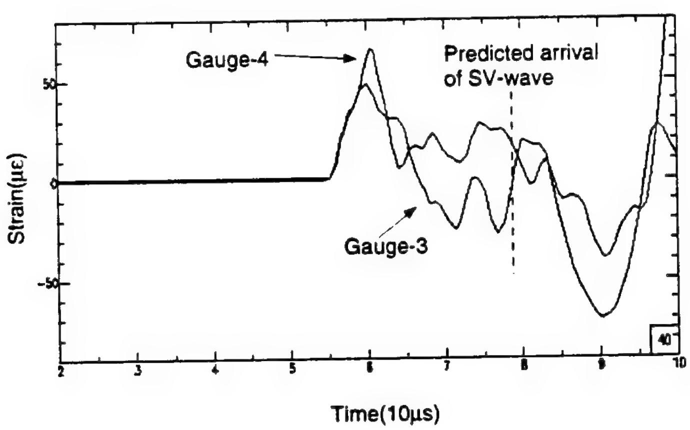


Figure 6 (a) The wave profiles from gages 1-4

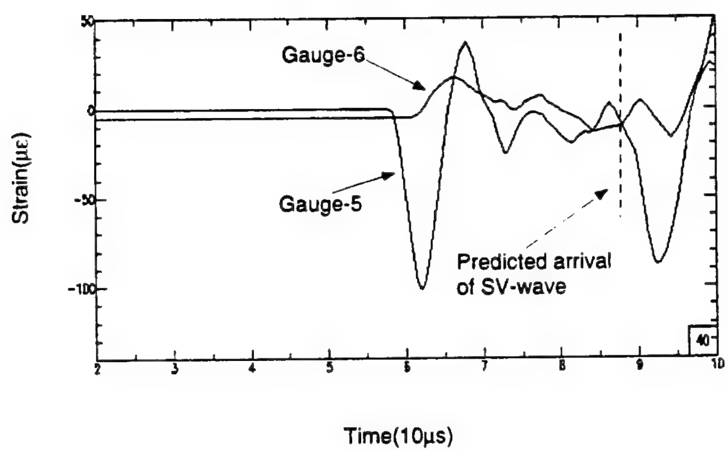


Figure 6 (b) The wave profiles from gauges 5 and 6

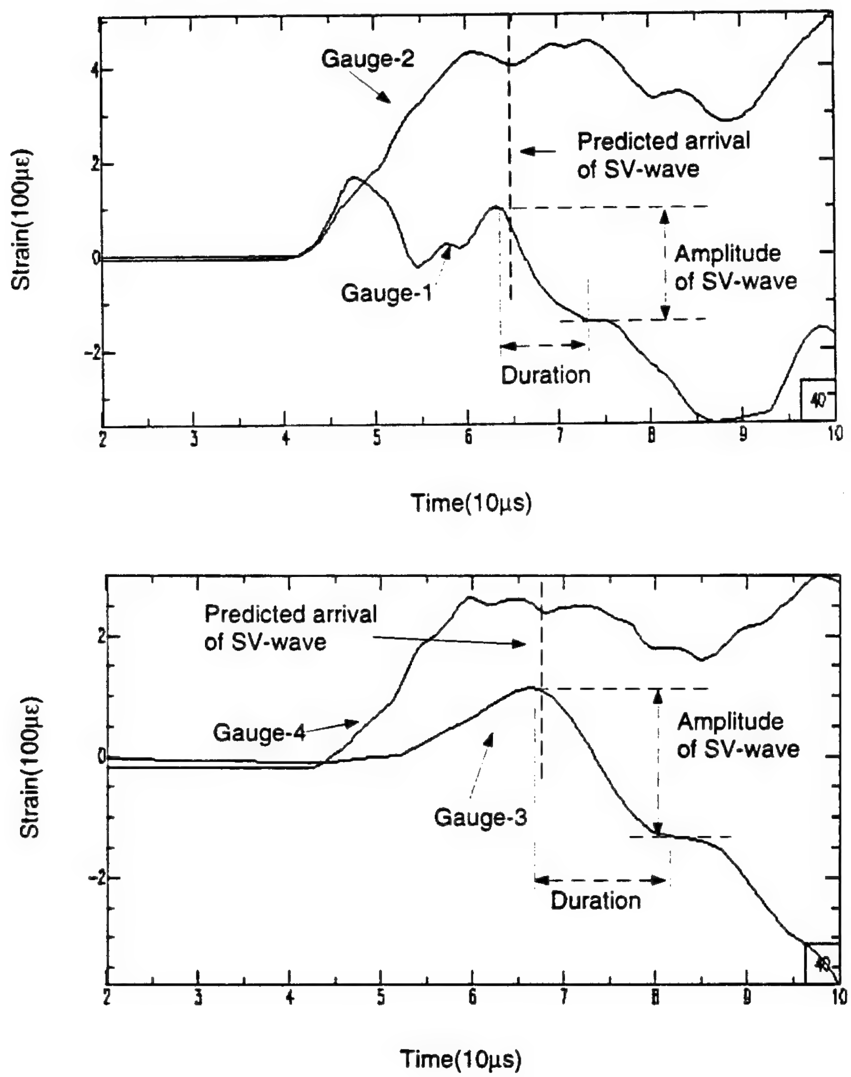


Figure 7 (a) The wave profiles from the gauge 1- 4

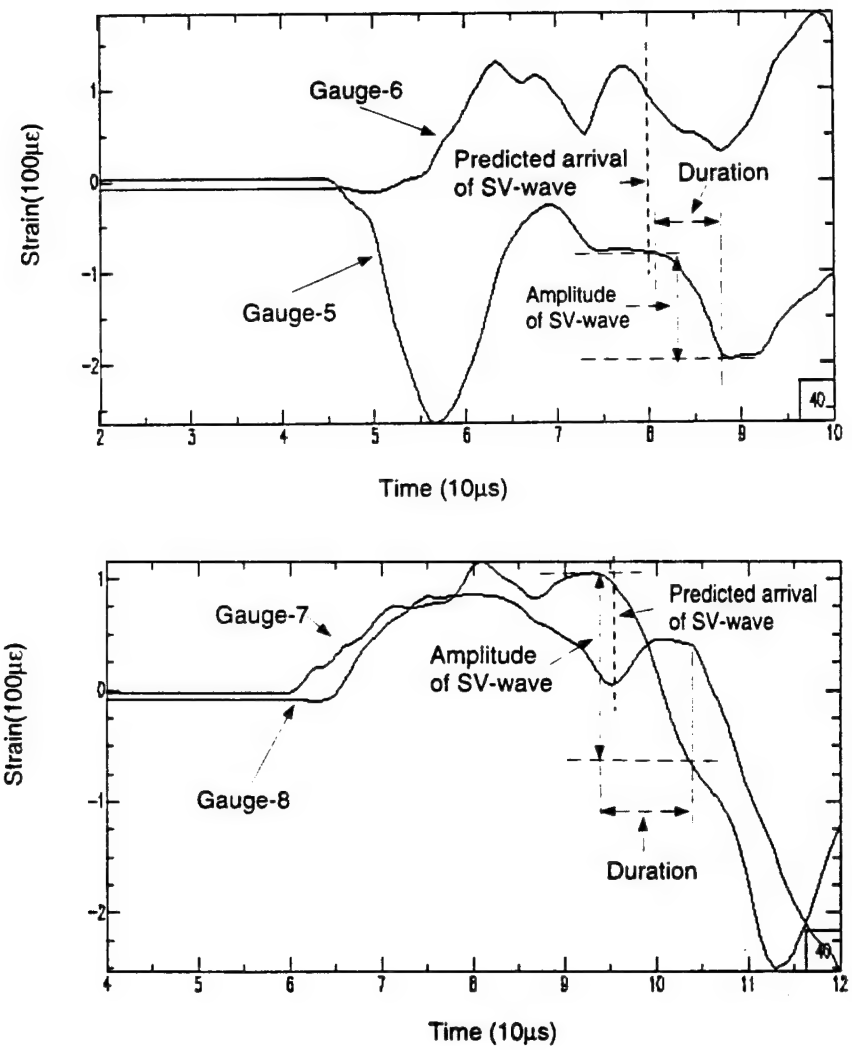


Figure 7 (b) The wave profiles from gauges 5 - 8

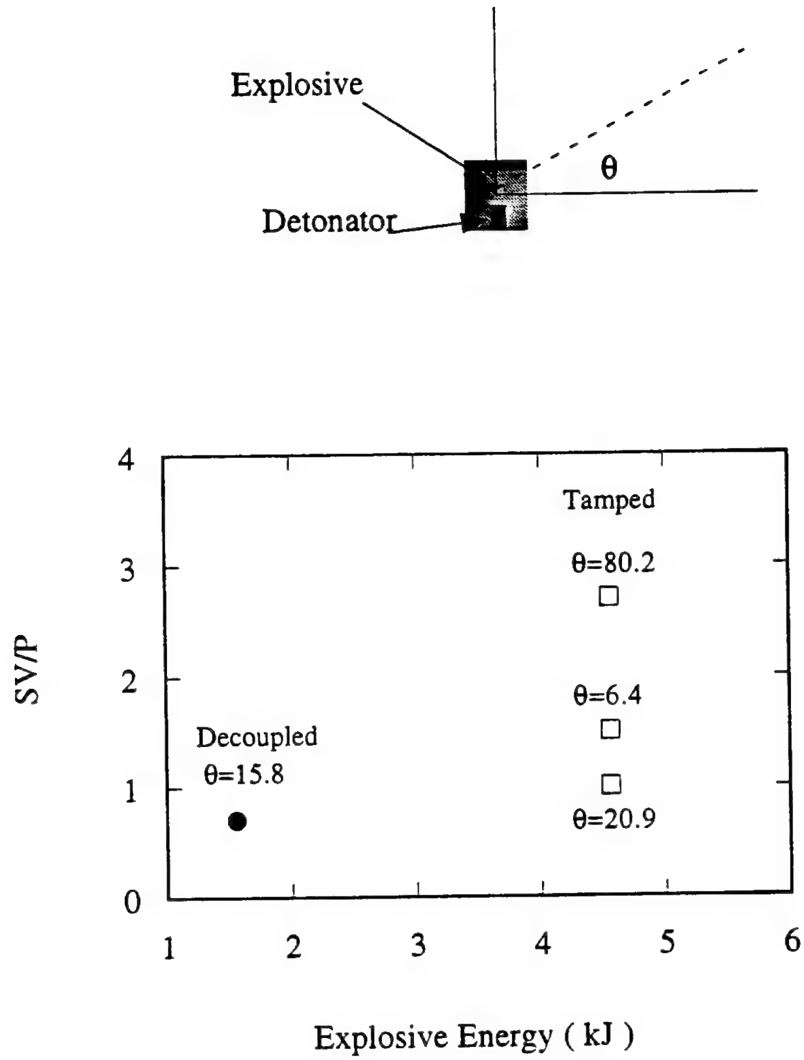


Figure 8 Ratio of SV- to P-wave particle velocity, SV/P, versus explosive energy

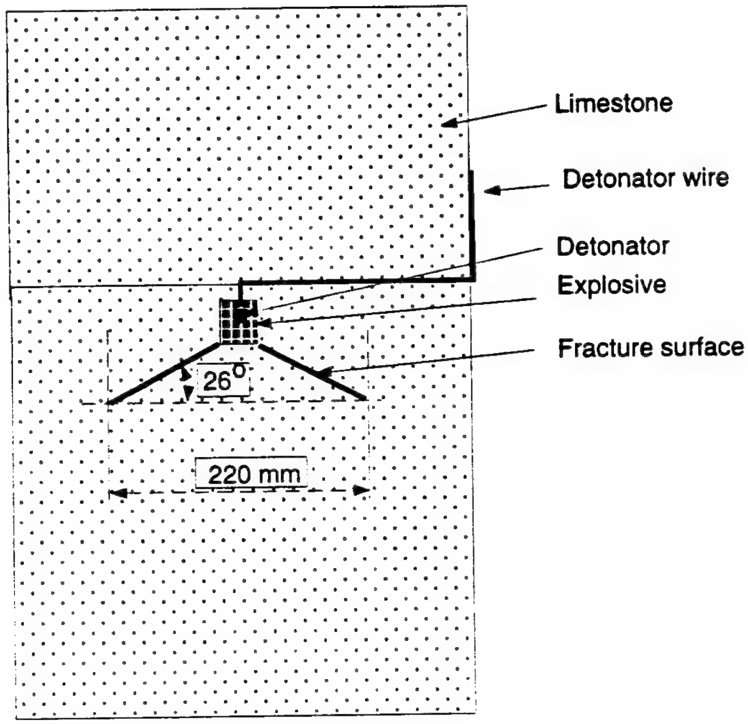


Figure 9 Profile of fracture surface from the tamped experiment.

derived expressions (Eqs. (26), (37), (39) and (41)), e.g., the strains along direction 1 induced by incident P-waves are always positive, and the strains along the direction 2 changed polarities with increasing P-wave incident angle as shown in Figures 6(b) and 7(b). The strains induced by incident SV-waves are much larger along direction 2 than direction 1 and are negative along direction 2 as shown in Figures 7(a) and (b). These experiment results verify that the method developed in this work can be used to monitor the P- and SV-waves generated from explosions in rocks.

From the records, it is straightforward to determine the SV-wave amplitude from the tamped experiment. It is difficult to get the SV-wave amplitude for the decoupled experiments, because it seems that there are several waves mixed with SV-waves. From the P- and SV-wave velocities of Bedford limestone (α = 4.9 (km/s), β = 2.8(km/s)), the expected S-wave arrivals are labeled on the records. The time difference between the expected and the recorded is less than $2\mu s$ for the tamped experiment, but it is hard to observe SV-wave arrival around the expected time for the decoupled experiment. The relationship between the ratio of average P-wave particle velocity to SV-wave particle velocity and the energy for the two experiments is shown in Figure 8. The experiment results are listed in the Tables 2 and 3.

The recovered samples indicate minimal damage occurred in the decoupled experiment near the cavity, but symmetric explosion-induced tensional fracture occurred in the tamped experiment. The profile of the fracture is shown in Figure 9. This tensional fracture is initiated by the interaction between shock waves and the cylindrical cavity surface at the corner and is further developed by the penetration of the high pressure explosion products. From the profile of the cavity used in Sterling explosion (Langston, 1983), this tensional fracture may occur around the intersection between the inner surface of the cylindric-like cavity and the free surface of the recrystallized salt and also around the pre-existing crack zone on the top of the cavity. These fractures should generate P- and SV-waves, and these waves can explain the polarity change of SV-waves and the second P-wave that appears to be generated beneath the bottom of the cavity.

From the records, the waves generated in the decoupled experiment contain relatively higher frequencies than those in the tamped experiment. The reasons may include: (1) the width of the shock waves acting on the inner surface of the rocks for the decoupled experiment is narrower than that of the shock wave for the tamped experiment. This is due to the difference between the initial dimensions of the explosive and the ratio of the volume of the explosive to the volume of the cavity. We intend to analyze this in more detail; (2) the elastic deformation radius may be larger for the tamped explosion than it is for the decoupled explosion.

4 Conclusions

From the first two experiments, we conclude:

1. The method we developed in this work can be used to monitor near source P- and SV-waves generated by explosions (with a smaller charge).

2. The waves generated in the decoupled experiment contain relatively higher frequencies than these generated in the tamped experiment. The corner frequencies of the signals need to be analyzed.

3. The efficiency of SV-wave generation from the tamped explosion is higher than that of the decoupled explosion. This may be caused by the large plastic deformation near the cavity and tensional fracture in the tamped experiment.

4. The explosion-induced tensional fracture which occurred in the tamped explosion may be used to explain some of the experimental results in the Sterling explosion.

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